

Overview of Charm Physics at RHIC

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Abstract. Heavy-quark production provides a sensitive probe of the gluon structure of nucleons and its modification in nuclei. It is also a key probe of the hot-dense matter created in heavy-ion collisions. We will discuss the physics issues involved, as seen in quarkonia and open heavy-quark production, starting with those observed in proton-proton collisions. Then cold nuclear matter effects on heavy-quark production including shadowing, gluon saturation, energy loss and absorption will be reviewed in the context of recent proton-nucleus and deuteron-nucleus measurements. Next we survey the most recent measurements of open-charm and J/ψ s in heavy-ion collisions at RHIC and their interpretation. We discuss the high- p_T suppression and flow of open charm in terms of energy loss and thermalization and, for J/ψ , contrast explanations in terms of screening in a deconfined medium vs. recombination models.

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CHARM PRODUCTION IN P+P COLLISIONS AT RHIC

Gluon fusion dominates the production of quarkonia, but the configuration of the produced state and how it hadronizes remain uncertain. Absolute cross sections can be reproduced by NRQCD models that involve a color octet state[1], but these models predict transverse polarization of the J/ψ at large p_T that is not seen in the data[2]. A general complication in understanding J/ψ results is the fact that $\sim 40\%$ of the J/ψ s come from decays of higher mass resonances (ψ' and χ_C)[3] - a feature that may contribute to the lack of polarization seen. One exception to this feature is the maximal transverse polarization observed for the Υ_{2S+3S} states[4]; where the lack of feed-down for these states may allow the polarization to persist.

J/ψ cross section measurements for p+p collisions at $\sqrt{s} = 200$ GeV from PHENIX[5] are shown in Fig. 1. These results, based on approximately 500 J/ψ s from the 2003 run, provide the baseline for both CNM studies in d+Au collisions and QGP studies in A+A collisions at RHIC, and are presently one of the limiting factors in obtaining precise nuclear modifications. However p+p data from the 2005 and 2006 runs will soon improve this baseline significantly with over 40,000 J/ψ s.

Open charm measurements at RHIC suffer from large systematics and statistical uncertainties due to the statistical subtraction methods that are used. Measurements by PHENIX and by STAR differ substantially[6] on the size of the charm cross section. Also the measured cross sections lie substantially higher than current theoretical predictions as shown in Fig. 2.

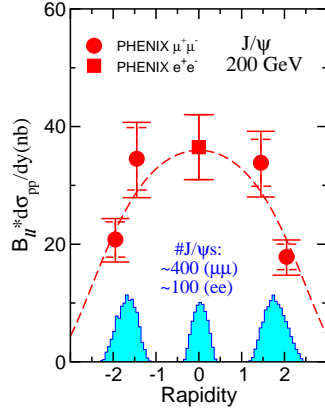


FIGURE 1. J/ψ cross section vs rapidity for 200 GeV p+p collisions at RHIC[5].

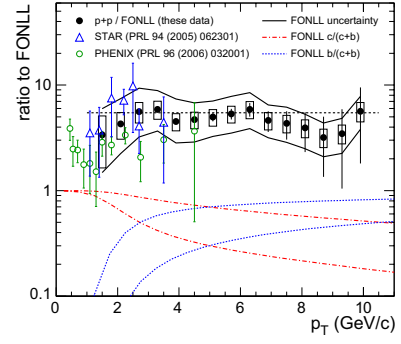


FIGURE 2. Open charm plus beauty cross section from prompt electrons divided by FONLL theory vs p_T for 200 GeV p+p collisions at RHIC[9].

NUCLEAR EFFECTS ON CHARM

When quarkonia are produced in nuclei their yields per nucleon-nucleon collision are known to be significantly modified. This modification, shown vs. x_F in Fig. 3 for 800 GeV p+A fixed target measurements and in Fig. 4 at RHIC energy, is thought to be due to several CNM effects including gluon shadowing, initial-state gluon energy loss and multiple scattering, and absorption (or dissociation) of the $c\bar{c}$ in the final-state before it can form a J/ψ .

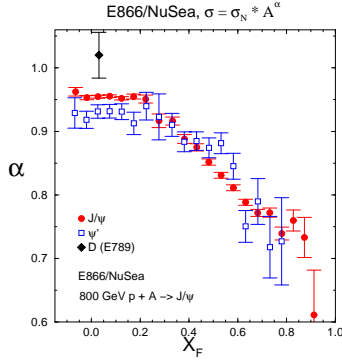


FIGURE 3. Nuclear modification factor α vs x_F for J/ψ and ψ' production in $\sqrt{s} = 38$ GeV collisions in E866/NuSea[7], and for D^0 from E789[8].

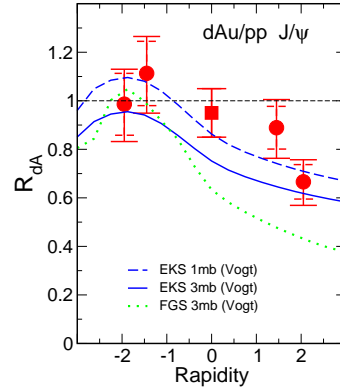


FIGURE 4. Rapidity dependence of the J/ψ nuclear modification factor, R_{dAu} for 200 GeV d+Au collisions at RHIC[5].

Shadowing is the depletion of low-momentum partons (gluons in this case) in a nucleon embedded in a nucleus compared to their population in a free nucleon. The strength of the depletion differs between numerous models by up to a factor of three. Some models are based on phenomenological fits to deep-inelastic scattering and Drell-Yan data[10], while others obtain shadowing from coherence effects in the nuclear medium[11, 12]. In addition, models such as the Color Glass Condensate (CGC)[13]

yield shadowing through gluon saturation pictures where the large gluon populations at very small x in a nucleus generate a deficit of gluons at small x .

In the final state, the produced $c\bar{c}$ can be disassociated or absorbed on either the nucleus itself, or on light co-moving partons produced when the projectile proton or deuteron enters the nucleus. The latter is probably only important in nucleus-nucleus collisions as the number of co-movers created in a p+A or d+A collisions is small.

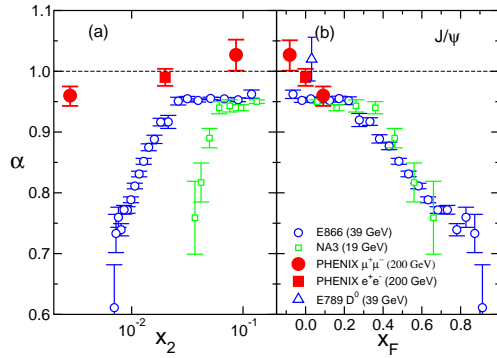


FIGURE 5. Test of scaling vs x_2 and x_F for J/ψ suppression data for three different collision energies. Data is from Refs.[7, 15, 5]

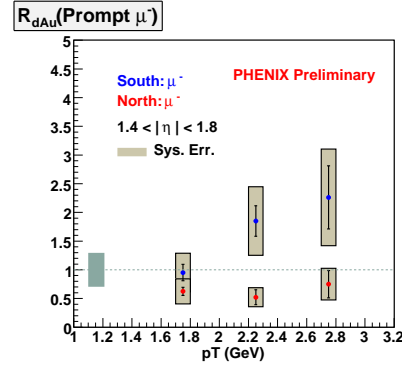


FIGURE 6. Nuclear dependence of heavy quark suppression vs p_T from single muons in PHENIX.

However, J/ψ suppression in p(d)+A collisions remains a puzzle given that one does not find a universal suppression vs x_2 as would be expected from shadowing, Fig. 5a; while vs. x_F the dependence is similar for all energies, Fig. 5b. This apparent x_F scaling supports explanations that involve initial-state energy loss or Sudakov suppression[14].

On the open-charm front, there are no substantial modifications seen at central rapidity in d+Au collisions, but for forward rapidity (shadowing region) - as shown in Fig. 6 - substantial suppression is seen, while some enhancement is seen at backward rapidity (Au-going direction).

J/ψ IN HEAVY-ION COLLISIONS - A QUARK GLUON PLASMA SIGNATURE?

One of the leading predictions for the hot-dense matter created in high-energy heavy-ion collisions was that if a deconfined state of quarks and gluons is created, i.e. a quark-gluon plasma (QGP), the heavy-quark bound states would be screened by the deconfined colored medium and destroyed before they could be formed[16]. This screening would depend on the particular heavy-quark state, with the ψ' and χ_C being dissolved first; next the J/ψ and then the Υ 's only at the highest QGP temperatures. The CERN SPS measurements[18] showed a suppression for the J/ψ and ψ' beyond what was expected from CNM effects - as represented by a simple absorption model constrained to p+A data. In addition to explanations involving creation of a QGP, a few theoretical models[17] were also able to explain the data without including a QGP, so the evidence that a QGP was formed was controversial.

The first measurements from PHENIX at RHIC in 2004 are beginning to yield results - see Fig. 8 for preliminary results for Au+Au and Cu+Cu collisions[19]. First it is important to understand what the normal CNM J/ψ suppression should look like in these A+A collisions. This is illustrated by the blue error bands for A+A collisions in Fig. 8 which represent identical theoretical calculations to the analogous blue error band in Fig. 7 for d+Au collisions. As can be seen the present d+Au data lacks enough precision to provide a good constraint on the CNM effects. As a result it is difficult to be very quantitative about the amount of "anomalous" suppression observed in A+A collisions, although there does seem to be a clear suppression beyond CNM for the most central collisions.

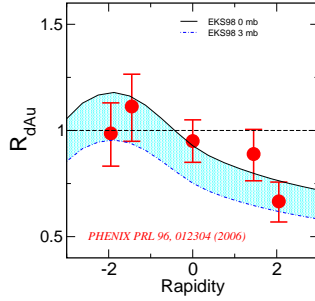


FIGURE 7. Results for J/ψ suppression in d+Au collisions[5] compared to a theoretical calculation that includes absorption and EKS shadowing[20].

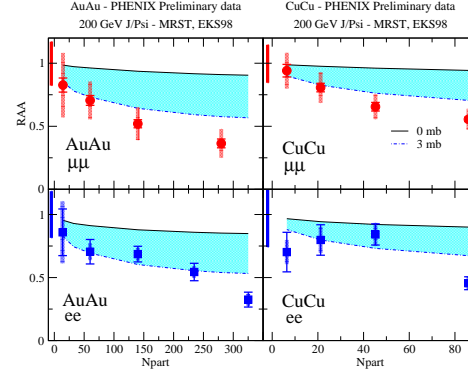


FIGURE 8. J/ψ suppression in Au+Au and Cu+Cu collisions for forward rapidity and central rapidity[19] compared to predictions for CNM from the same calculations as shown in Fig. 7[20].

On the other hand, all of the models[17, 21, 22] that were successful in describing the lower energy SPS data over-predict the suppression compared to the preliminary data at RHIC - unless a "regeneration" mechanism is added as was done by Rapp[22] and by Thews[23]. The regeneration models assert that if the total production of charm is high enough then densities in the final state will be sufficient to have substantial formation of J/ψ s from the large number of independent charm quarks created in the collision. This production mechanism was almost insignificant at SPS energies but at RHIC may be substantial. This leads to a scenario in which strong screening or dissociation by a very high-density gluon density occurs to a level of suppression stronger than the RHIC data shows, but the regeneration mechanism compensates for this and brings the net suppression back up to where the data lies. This is shown in Fig. 9.

An alternative interpretation of the preliminary results, sequential screening, is given by Karsch, Kharzeev and Satz[24]. In this picture, they assume that the J/ψ is never screened, as supported by recent Lattice QCD calculations for the J/ψ - not at SPS nor at RHIC. Then the observed suppression comes from screening of the higher-mass states alone (ψ' and χ_C) that, by their decay, normally provide $\sim 40\%$ of the observed J/ψ s. This scenario is consistent with the apparently identical suppression patterns seen at the SPS and RHIC shown in Fig. 10.

As a result we are left for the moment with two different scenarios that provide explanations for the RHIC A+A data. Both include the QGP in their picture, either

through color screening in the QGP or through severe suppression of the J/ψ by a very high gluon density. Further tests from the data will be necessary to clarify the picture. Regeneration models predict narrowing of both the rapidity and p_T distributions, but so far the preliminary data shows little or no change in the rapidity shape from ordinary p+p and only a hint of narrowing of the p_T . We are also trying to extract a measurement of flow for the J/ψ , since emerging results for single charm are beginning to show flow and the J/ψ 's, if they were from regeneration, would inherit this flow. These tests await the more precise final analysis of the 2004,5 Au+Au and Cu+Cu data; and higher statistics runs for Au+Au and d+Au in the near future.

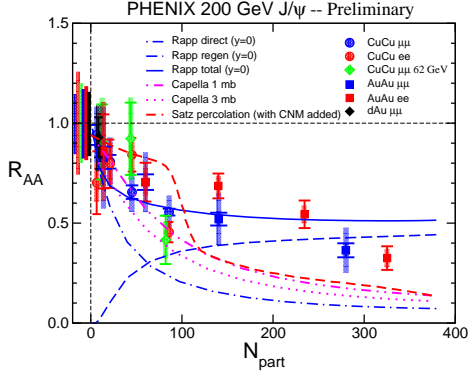


FIGURE 9. Theories that agree with SPS data do not agree with RHIC data, unless regeneration is added as in the Rapp (solid blue) curve.

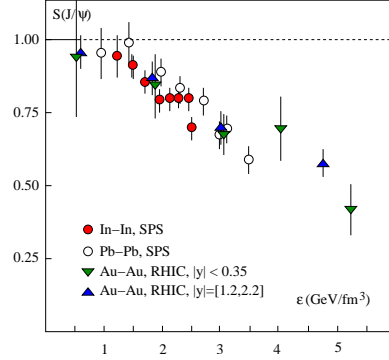


FIGURE 10. Universal dependence on energy density of J/ψ suppression measurements at RHIC and at the SPS[24].

OPEN CHARM IN AU+AU COLLISIONS

In Au+Au collisions, open charm (and beauty) together, are suppressed due to energy loss in the dense medium, with gluon densities per unit rapidity of up to 1000 inferred in some theoretical analysis. However, as shown in Fig. 11, calculations that include both radiative and collisional energy loss[25] predict too small a suppression when both charm and beauty are included. Flow has also been observed for heavy quark production. As shown in Fig. 12, the flow is similar to that of light quarks at small p_T , but at higher p_T the data with large uncertainties hints at vanishing flow, consistent with simple expectations that higher p_T charm simply punches out of the medium and never thermalizes.

SUMMARY

Substantial uncertainties remain in the understanding of charm production cross sections, and the polarization of charmonia. There are also a number of cold nuclear matter effects that influence their production in nuclei and cloud our understanding of the suppression seen in nucleus-nucleus collisions. Two competing pictures are able to explain the J/ψ suppression seen in nucleus-nucleus collisions at RHIC - one involving sequential screening in the plasma of the various charmonia states; the other with strong

dissociation of all charmonia states by a dense gluon field but recombination of independently produced charm quarks. For open charm, the the energy loss observed in the dense medium from nucleus-nucleus collisions is larger than that expected from theoretical models that include radiative and collisional energy loss of both charm and beauty. Higher statistics data with higher luminosity runs as well as RHIC vertex detector upgrades will enable more precise data in the future that will give a clearer understanding of the rich physics in charm production.

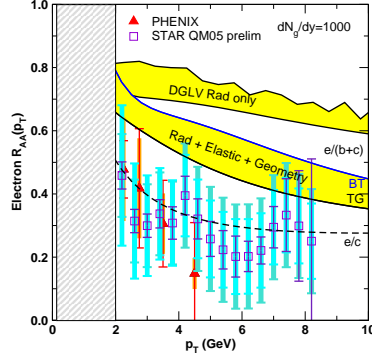


FIGURE 11. Energy loss calculations compared to open heavy (charm + beauty) data vs p_T [25].

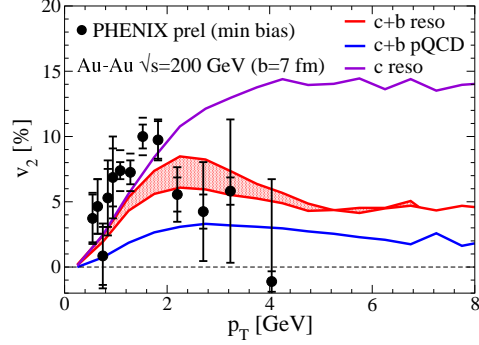


FIGURE 12. Elliptic flow of open heavy (charm + beauty) compared to Rapp calculations[26].

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